Report for 2002UT1B: Source Water Protection Assessment Tools Development

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Report Follows:

Research Project Synopses

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Introduction

Source water protection assessments provide information about potential contamination risks to drinking water supplies in a watershed. They may be done initially to characterize the drinking water contamination risks in watershed. They may also be done to inform planners about the potential impacts of development and changes in watershed activities. This information may be used by watershed managers to rank risks and to prioritize activities that will protect the drinking water supplies. Protective measures may be expensive. Land use restrictions to protect water quality can extensively alter the potential for development of private property and diminish property values. These potential impacts of management make it very important that source water assessments correctly identify potential risks and present a scientifically credible evaluation of the magnitude of the risk so that the monetary and social costs of protective management can be minimized. Simultaneously, management activities must effectively protect public health. It is vital that sound scientific principles are used to direct the assessment approach and that arbitrariness is avoided. It is also important that the assessment be completed in a timely way and that the costs of the assessment are reasonable. To control costs, available information should be used and the need to collect new data should be minimized. Assessment tools are needed that will help watershed managers appropriately apply the scientific principles of pollutant transport while maximizing the use of available information.

A computerized source water assessment tool is being developed to assist drinking water watershed managers in assessing the susceptibility of drinking water supplies to pollution from current and future activities in the watershed. The tool development has focused principally on providing assistance with the pollutant source inventory process, on modeling surface runoff and stream flow processes, and on the fate and transport of pollutants related to these processes. The current version of the surface water pollutant transport model is called the Utah Pollutant Transport Model (UPTraM). The details of the development of the pollution source inventory portion of the tool and UPTraM were described in the FY 2000 and FY 2001 annual reports. Moncur (Moncur 2002) also described the development of the source inventory system, UPTraM, and the associated graphical interface for the assessment tool.

The Source Inventory and Other Data

The source water protection assessment tool includes a potential pollution source inventory database and a pollutant chemical properties database. A database of information for model operations (e.g., digital elevation models (DEM), river reaches, land use, etc.) is also provided. A graphical user's interface and models to simulate the transport and fate of water-borne pollutants form the core of the tool. Figure 1 illustrates the relationship of the major components of the assessment tool. The tool provides assistance in finding the appropriate data for the potential source inventory and transport modeling.

The watershed inventory is a user input database of the current and/or future potential contamination sources within the watershed. A quick-reference database of chemical properties, including toxicity information, is provided to help the user identify and prioritize potential pollution sources. The chemical properties within the quick-reference database are physical and chemical properties for EPA's National Primary Drinking Water Regulation listed compounds (USEPA 2003).

Ranges of loading rates for total and fecal coliforms and nitrogen and phosphorus are also available in the database. GIS land use coverages that delineate urban and agricultural land use practices may be used with loading rate data to evaluate pathogen risk, as indicated by coliforms, from urban runoff, animal feeding operations, and pastures. Potential nutrient inputs to reservoirs may be estimated using the nutrient loading data. Land use coverages may be available from state natural resource management or environmental protection agencies or the National Land Cover Dataset (NLCD) (http://edcwww.cr.usgs.gov/programs/lccp/nationallandcover.html). In Utah, land use data for much of the state is maintained by the Department of Natural Resources, Division of Water Resources.

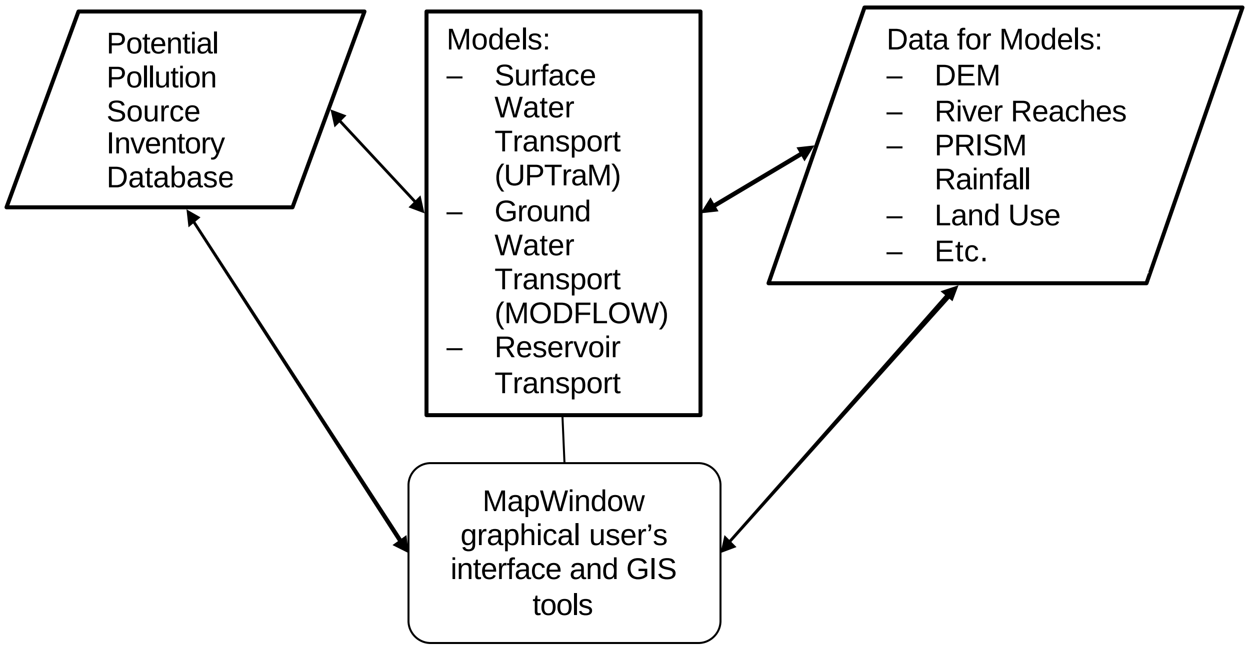

Figure 1. Source Water Assessment Tool schematic.

The Graphical User's Interface

The complete graphical user's interface for the tool will facilitate the operations of the databases and the various models that make up the tool. The current, fully functional components of the graphical user's interface support the databases and the surface water transport model. The components of the surface water protection assessment tool are: (1) the main GIS graphical interface, (2) the GIS coverage project builder, (3) the Potential Contaminant Source (PCS) inventory data management utility, (4) the transportation accident data form, and (5) the pollutant transport and degradation/volatilization analysis model, UPTraM. To get the surface water program started, the user must obtain and input the necessary GIS coverages of the watershed of interest. These coverages include a watershed boundary shape file, a grid DEM, and an average annual precipitation grid. The user may also add a land use shape file and grid, a river reach shape file, and a major road shape file. All of these can be displayed graphically through the MapWindow part of the GIS interface. The input GIS coverages can be used as a platform for the input of PCS locations and for model analysis visualization. Once these GIS coverages are input via the user interface program lead project builder, the user can start to inventory a watershed for PCSs.

Figure 2 shows the SWPAT MapWindow graphical interface for surface water transport. The GIS coverages shown in Figure 2 are a grid DEM, an animal feeding operation inventory shape file, an above ground tank inventory shape file, and a watershed boundary shape file (green). Other GIS datasets that are included in the table of contents panel on the left but are not active in

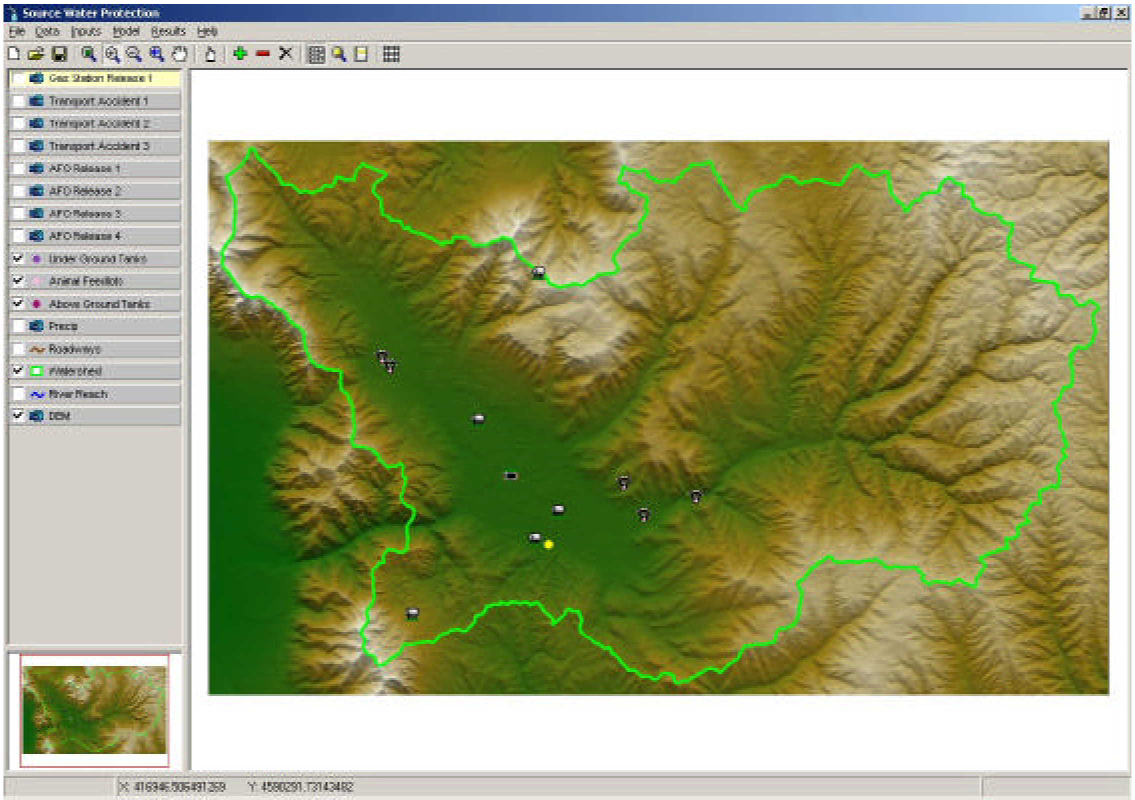

Figure 2. The SWPAT MapWindow graphical interface for surface water transport.

this display are the annual average precipitation grid, a major roads shape file, an EPA level 3 river reach shape file, and several accident scenario shape files.

When starting a new project within the assessment tool, the program will guide the user to input the required GIS data sets for use in UPTraM. The data sets that must be input are: a grid DEM, a precipitation grid, a river reach shape file, a watershed boundary shape file, and a land use grid. The land use grid needs to be condensed into the five general land use groups to be used by the tool, namely (1) water, (2) urban, (3) pasture, (4) non-pasture agriculture, and (5) rangeland/forest areas. The user selects the GIS coverage that is going to be input and the program prompts the user with another form that allows the user to browse the computer hard drive for the desired information. The inventory requires the user to input PCSs for geographical placement within the watershed and associated chemical property information from the quick-reference database. There are eight different PCS types that can be inventoried. These different PCS types are:

1. Above ground tanks
2. Underground tanks
3. Animal feeding operations
4. Transportation accidents
5. Landfills
6. Superfund sites

7. Chemical Companies
8. Hazardous waste sites.

The Surface Water Transport Model, UPTraM

The surface water transport model is a risk-ranking assessment tool that models source water protection scenarios without using arbitrary protection zones. The tool has been created using a GIS framework. The user has the option of incorporating fate processes such as volatilization of organic pollutants and dieoff of fecal indicator bacteria into transport simulations.

The development of geographic information systems (GIS) and digital elevation models (DEMs) has provided an unprecedented opportunity to describe the pathways of water movement in a watershed. Visualization of the locations of PCSs relative to stream locations and topography within a watershed along with the possible route or routes of pollutant transport provides watershed managers with insight that can help in the risk ranking process and in selecting or designing pollution control mechanisms. GISs provide an elegant mechanism for displaying this kind of information as well as facilitating models for routing water and associated pollutants through the watershed to the drinking water treatment plant.

DEM databases for the United States provide data that allows the extraction of drainage networks from the DEMs (Band 1986; O'Callaghan and Mark 1984). Topographic structure, watershed delineations, and overland flow paths derived from DEMs can be transferred to a vector-based GIS for further analysis. (Garbrecht and Martz 1997) have developed a procedure for assigning flow direction over flat surfaces in raster DEMs. TOPMODEL (Beven et al. 1995; Beven and Kirkby 1979) used DEM topographical information in the simulation of runoff from natural watersheds and from agricultural watersheds with tile drain systems (Kim et al. 1999)

(Tarboton 1997) developed a procedure for the representation of flow direction and calculation of upslope areas using rectangular grid DEMs. Rather than representing flow in one of the eight possible directions from a grid cell to an adjacent or diagonal neighbor (D8) this procedure represents flow direction as a vector along the direction of the steepest downward slope on eight triangular facets centered at each grid cell. An infinite number of flow directions, represented as an angle between 0 and 2π are possible, so this procedure is named $D\infty$. Flow from a grid cell is shared between the two, downslope grid cells closest to the vector flow angle based on angle proportioning. Drainage area is accumulated using this model that has two flow paths from each grid cell based on the angle proportions. This procedure has been included in the Terrain Analysis using Digital Elevation Models (TauDEM) software (Tarboton 2000; Tarboton 2002) that is used as a basis for the Surface Water Protection Assessment Tool (SWPAT) developed here. Overland flow and the transport of contaminants simulated in the assessment tool are routed using the $D\infty$ surface flow model. Much of the information necessary to support water routing simulation including DEMs <http://mcmcweb.er.usgs.gov/status/dem_stat.html>, stream shape files, and precipitation data (SCAS and OCS 2002) are readily available through the internet for nearly all of the United States.

In UPTraM, the contaminant concentration in water leaving the contaminated area is the saturation concentration for soluble contaminants. Coliform concentrations leaving contaminated areas are the high, medium, or low (e.g., 10^9, 10^6, 10^3/100 mL) export concentration for a given land use that is selected by the user. The contaminants that move with surface water may be subject to reduction due to various processes, such as die off (in the case of coliforms) or volatilization (in the case of chemical spills). We have incorporated the capability to model first order decay in UPTraM to represent these processes.

A concentration limited accumulation function is then used to evaluate the contaminant concentration downslope from the source. Flow is written

$$q(x,y)=a[r_s] \tag{1}$$

Over the substance supply area, concentration is at the threshold C_{sol}.

If i(x, y) = 1

$$C(x,y) = C_{sol} \tag{2}$$

$$L(x,y) = C_{sol}\, q(x,y)$$

Where L(x,y) denotes the load being carried by the flow (per unit width). At remaining locations the load is determined by accumulation of this Load L with decay

$$L(x,y) = \sum_{k \text{ contributing neighbors}} p_k d(x_k, y_k) L(x_k, y_k) \tag{3}$$

Concentration is determined by

$$C(x,y) = L(x,y)/q(x,y) \tag{4}$$

The denominator in (4) includes the base flow for stream locations, but includes only surface flow for off-stream locations.

The Ground Water Transport Model

Development of the ground water transport portion of the tool is nearing completion. The ground water-modeling component will consist of a ground water quantity model and a ground water quality model. The ground water quantity model will be used to simulate ground water movement in an aquifer. The ground water quality model requires the output of the ground water quantity model. The ground water quality model will simulate pollutant movement in the ground water system. Output from the quality model will be provided in a GIS data format, which can be analyzed by the watershed manager using a software interface.

Figure 3 shows the major components of the ground water modeling part of the source water assessment tool. The ground water quantity-modeling component is MODFLOW and the pollutant transport component is called <u>M</u>odular <u>T</u>hree-<u>D</u>imensional <u>M</u>ulti-<u>S</u>pecies <u>T</u>ransport (MT3DMS). The US Geological Survey developed MODFLOW and MT3D, a predecessor to MT3DMS. The US Army Corps of Engineers developed the MT3DMS model. These models are available, free of charge, and are widely accepted in ground water hydrology and engineering practice. MODFLOW is a modular finite difference model that simulates ground water flow. MODFLOW is coded in FORTRAN and requires a specific data input format. The major inputs required for running MODFLOW are:

- Model grid size and aquifer's thickness
- Model area soil hydraulic conductivity
- Recharge to aquifers (area and point source)

- Ground water boundary conditions
- Rivers stages and river cell location (if river package is used)

The major outputs from MODFLOW are the predicted ground water elevation or head for each grid cell in the model along with a water budget (mass balance) for each grid cell. These two outputs can be used as inputs to run MT3DMS. MT3DMS takes into account the affect of advection, diffusion, dispersion, reaction and retardation on pollutant transport. It uses the flow field developed in MODFLOW. The major input data are:

- Ground water head and water mass budget generated by MODFLOW
- Model grid size and aquifers thickness
- Effective soil porosity at each model cell
- Advection numerical solver parameters
- Soil dispersion and diffusion effect parameter (longitudinal dispersivity, horizontal/ transverse dispersivity, vertical dispersivity and diffusion coefficient)
- Pollutant loading source location, type and rate

The major output form MT3DMS is an unformatted file of pollutant concentrations for the model grid cells for each contaminant species at a specified time. We can modify the MT3DMS code to generate a contaminant mass budget at each cell.

The data needed for the ground water models is usually available on the Internet from the USGS or other government agencies. Boundary conditions could be established with a prior knowledge of the watershed. The types of boundary conditions MODFLOW uses are:

- Constant head boundary, e.g., a river or a reservoir
- No flow boundary, e.g., an impermeable layer such as mountain bedrock
- Constant flux, e.g., a constant flux of water, such as a stream inlet or ground water recharge from neighboring aquifers

The most important data needed are the hydraulic parameters (such as conductivity) of the aquifer material. If that is not available, an assumption could be made based on prior knowledge of hydraulic conductivity values for different, common types of soils. It is often the case that there has not been enough geological investigation done to describe the soil type or hydrogeological characteristics for the whole model area. In that case, interpolation algorithms can be used to get an approximation of hydraulic parameters.

The thickness of an aquifer could be estimated using well driller's logs maintained by the state water rights department. Alternatively, the user can decide the thickness of the aquifer layer to be modeled and the bottom elevation of the layer can be calculated by subtracting the assumed thickness from the elevation indicated by the DEM.

The initial head value could be assumed to be the ground surface elevation in a steady state simulation.

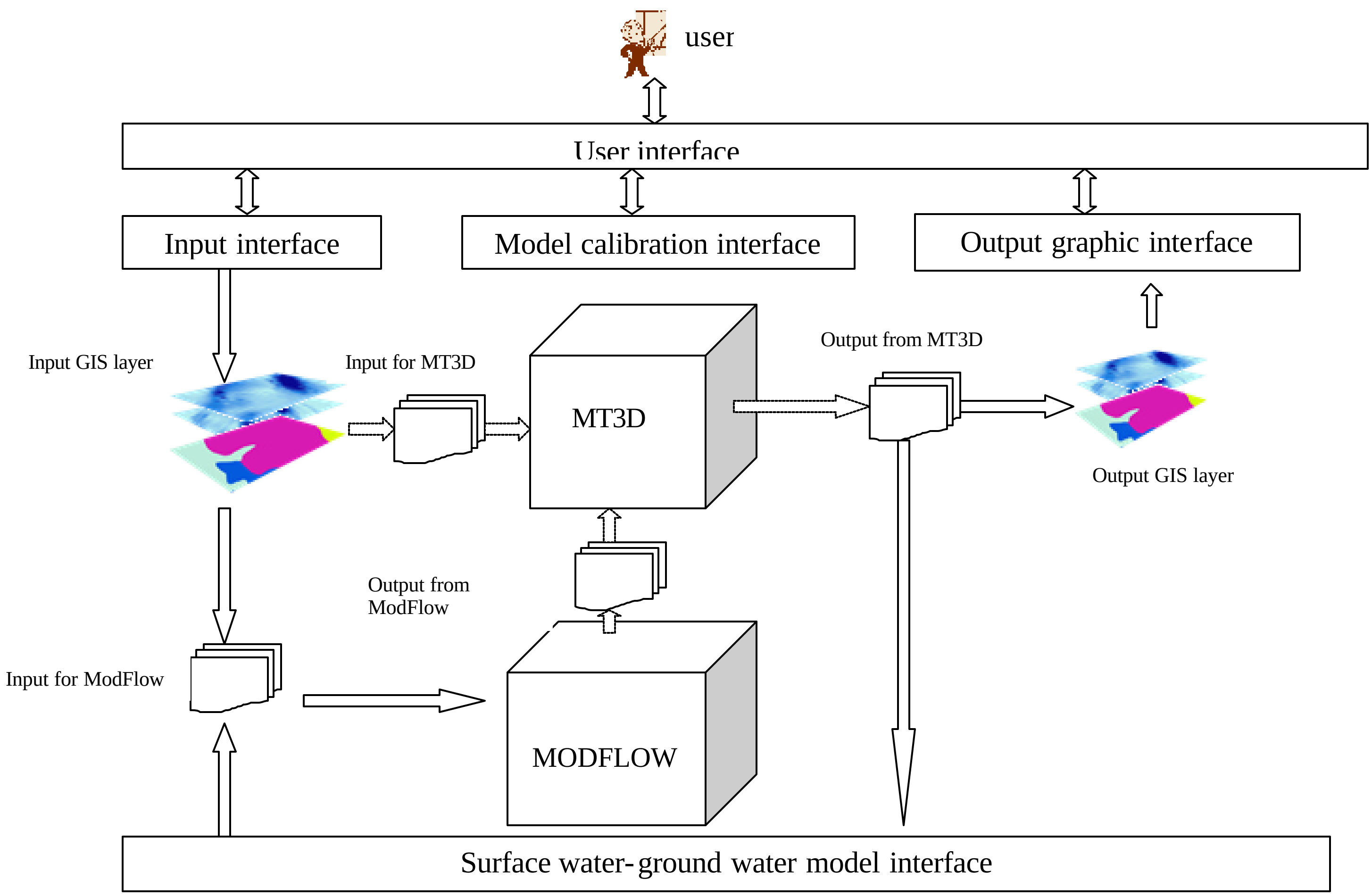

Figure 3. Schematic structure of the ground water modeling component

Ground water recharge data is created based on analysis of the annual precipitation grid, well pumping data and base flow analysis at existing gage stations. Because of the scarcity of data, a recharge data file may need to be generated by multiplying the precipitation grid by a factor derived from the hydrograph analysis.

The required data may not be readily available. The data that is available may not be in the format necessary to run the ground water models. An interface has been developed which generates the required files for MODFLOW with minimum input requirements. Hydraulic conductivity can be interpolated for the entire watershed if the user provides hydraulic conductivity values for a few points in the watershed. The user can manually delineate a watershed using a map displayed on a computer monitor and a computer mouse. Boundary conditions are also entered using the graphical interface.

MT3DMS

The major data file needed by the MT3DMS is the contaminant source. Area sources (cropland, pasture) and point sources (septic tanks, leaking underground storage tanks) can be modeled. Area source location data can be generated from land use GIS data (these data are widely available on the internet). Land use GIS data should be converted to an ASCII grid file. This is done manually using ArcInfo tools. Point sources can be manually added into MT3DMS data file directly. The user is required to provide all the loading rates and source types for all sources.

The other data needed are soil dispersivity values in 3 dimensions; these values are estimated based on soil type in the watershed area. Initially, a single value may be used for an entire watershed.

An interface similar to one used with MODFLOW is being developed to assist the user in generating input data files for MT3DMS.

Ground Water Interface to Surface Water Model

The final out put from the ground water component is obtained as pollutant-loading rate at specified stream locations or reservoir. It is then incorporated into the surface water model by routing the pollutant mass loading along the stream network.

Challenges

Calibrating the model is the most challenging task in operating the ground water flow model. It is necessary for the modeler to calibrate the model to get reasonable and acceptable results. If enough data is available, output from MODFLOW, i.e., head and base flow at certain points, could be compared to the actual field data. If there are discrepancies between model predictions and field observations, some model input parameters such as hydraulic conductivity and recharge need to be adjusted. The same logic applies to the ground water quality model. To implement this, more data is needed and a more advanced interface is needed. The user has to iterate the model runs until the discrepancies decrease to an acceptable level. This effort is labor and time intensive. If the model calibration is not within strict tolerance limits (i.e., 5 %) the model may generate erroneous results or the numerical solver does not converge. A balance between user interface software complexity and efficiency needs to be defined.

Another major challenge in completing the source water assessment tool is designing and programming the interaction of the surface water model and the ground water model. The surface water quality model has a different setting (resolution) than the ground water model including grid cell size or modeling area. In addition, the stream network that is considered in the ground water model is different from that for the surface water model. The ground water model only simulates major streams that have base flow throughout the year. The routing method in the ground water model needs to be refined. The combination of these models is a current focus of the project.

An On-Site Wastewater System Database for Utah

A major challenge in source water protection programs is collecting information about the density of on-site wastewater systems in the watershed. It is often assumed that on-site systems contribute nitrate, other nutrients, and pathogens to drinking water supplies. A quantitative assessment of the amount of on-site wastewater-associated contamination actually reaching source waters is rarely available. Watershed managers are often left to guess about whether more on-site wastewater systems should be allowed in drinking water watersheds. The Utah Department of Environmental Quality, Division of Water Quality has requested that a state-wide database system be implemented so that management information can be more readily available to local health department personnel and to state water quality managers. Because of the compatibility of this goal with the source water protection assessment mission of the present project, database development has been included in the project.

Selected commercially available on-site system databases were evaluated early in the project. We concluded from our evaluation that none of the databases that were evaluated were likely to be accepted by local health department personnel in Utah. It was our judgment that each of these databases required conformation of the data collection and data entry processes that would not be acceptable. Telephone interviews with personnel of health departments outside of Utah that had purchased these programs revealed that none of these potential users were, in fact, using the programs that they had purchased.

A database that was being actively used, and that was perceived as being very valuable, was a Microsoft Access database created by the Whatcom County, Washington, health department. Apparently, the database was well accepted because it was consistent with the practices of those using it and the users were actively involved in designing it. Following this model, we have worked closely with two of the 12 local health departments in Utah to construct a database program. Personnel from the Wasatch City-County Health Department and Tricounty Health Department have worked closely with student programmers to build the database. Data entry formats (Figures 4-8) are consistent with Utah on-site wastewater rules and are based on paper formats that have been used by the Wasatch City-County Health Department or the Tricounty Health Department. Representatives from the Health Departments to the state-wide Conference of Local Environmental Health Administrators Wastewater Subcommittee will be asked to evaluate the database program in each of their Departments and provide suggestions for improvement, in general. They will also be asked to indicate what would be required to customize the program for use in their Department. Workshops are planned to involve personnel from various Health Departments in creating the final version or versions of the database and to train them in the use of the program.

Conclusions

The ease of obtaining GIS data combined with the development of a computational procedure for representing flow direction and calculating upslope areas using DEMs (Tarboton 1997) has opened the opportunity for simulating pollutant transport in watersheds in a new way. This approach is realistic, scientifically credible, and requires relatively little data. Simplifying assumptions about chemical pollutant loading into storm water and pollutant fate processes allows the use of chemical property data from the literature to estimate contaminant concentrations at a point of extraction for drinking water for drinking water use. Similarly, estimated coliform loading and die-away rates allows the estimation of coliform concentrations from possible sources in a watershed. This approach facilitates delineation and ranking of zones of potential contamination based on the risk that possible contamination sources within those zones present to a drinking water treatment and distribution system. The SWAPT helps managers to determine if other methods of analysis or additional system monitoring are needed to increase confidence in determining a possible contaminant source's threat to source water quality.

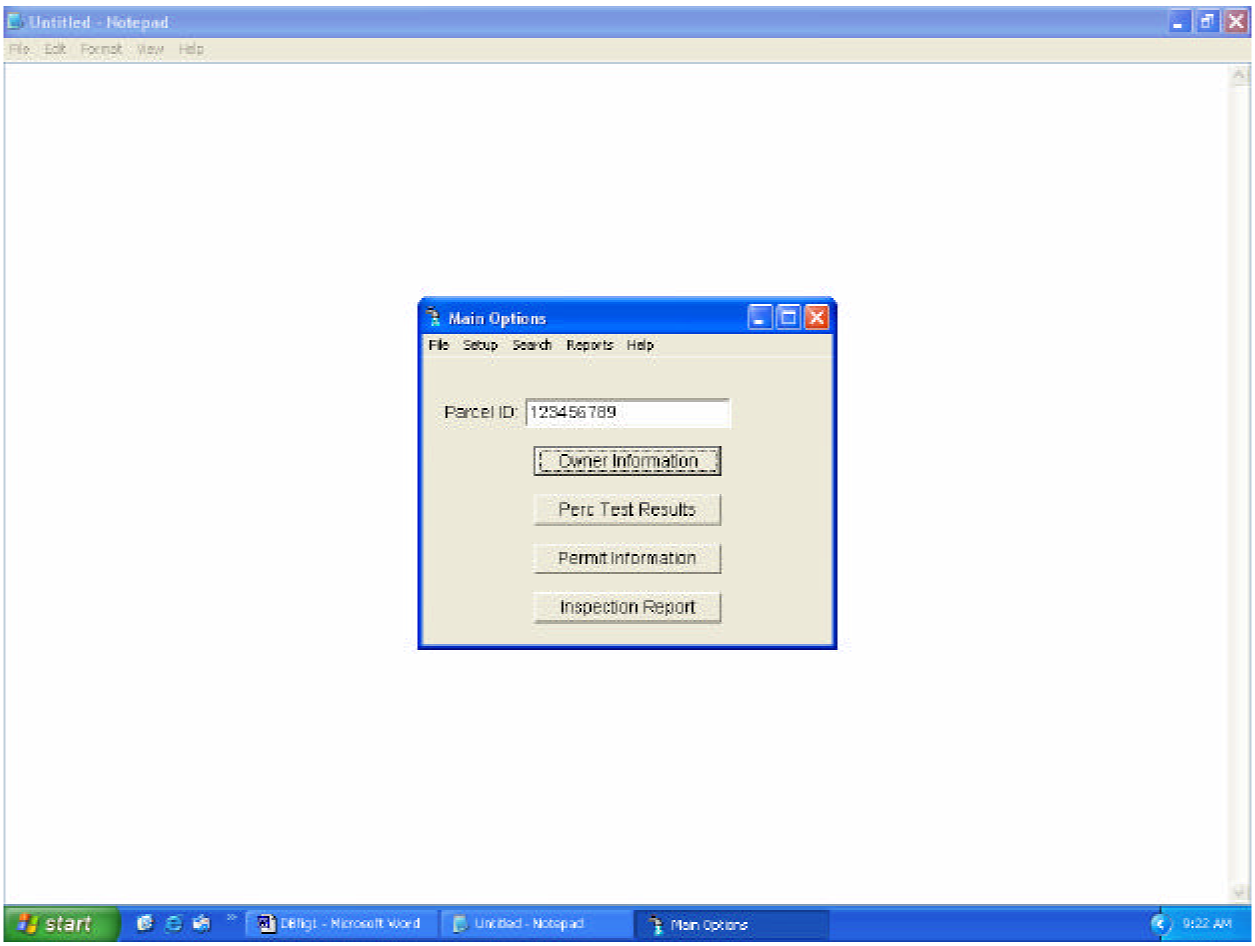

Figure 4. Main Options menu for the On-Site Database.

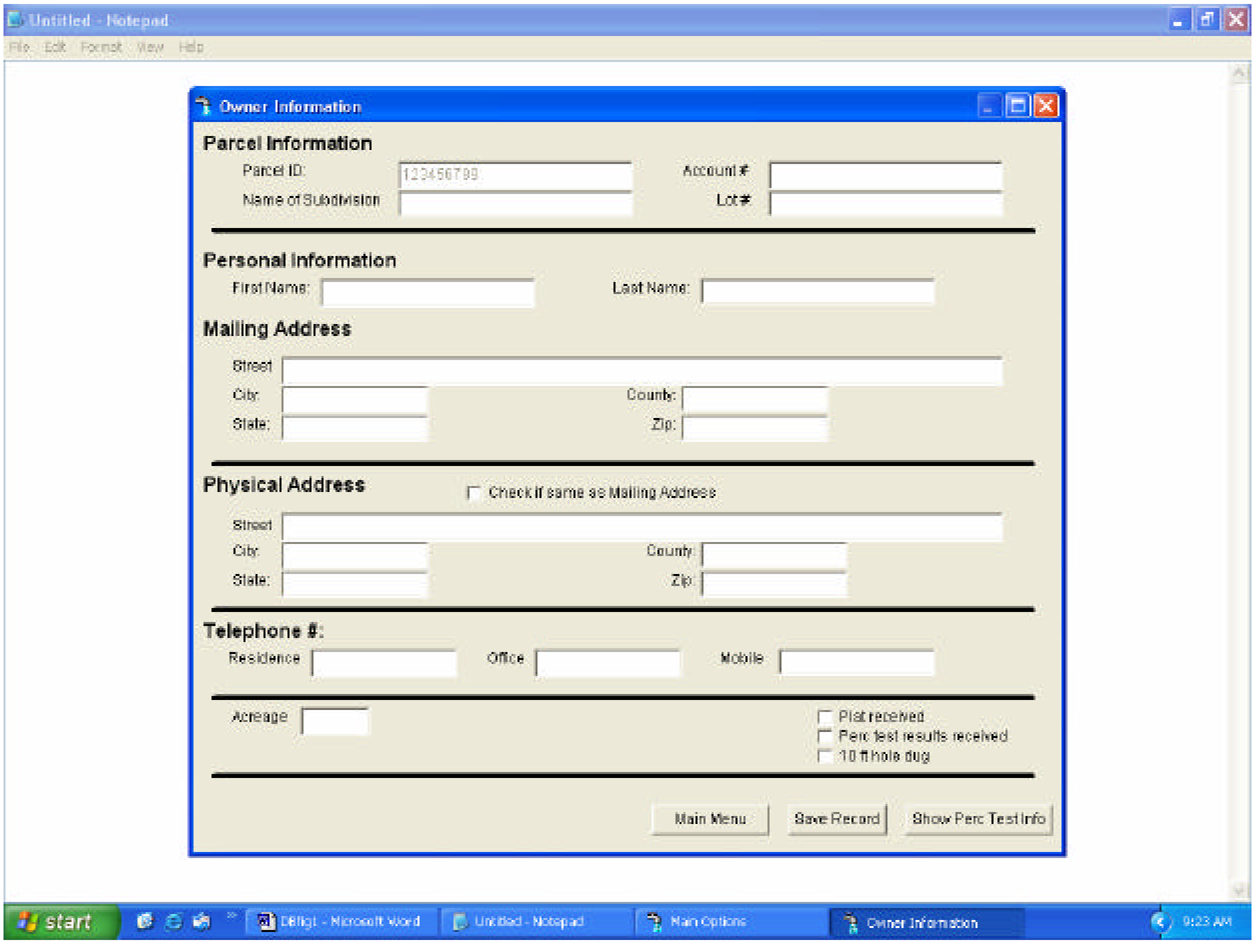

Figure 5. On-Site Database owner information input form.

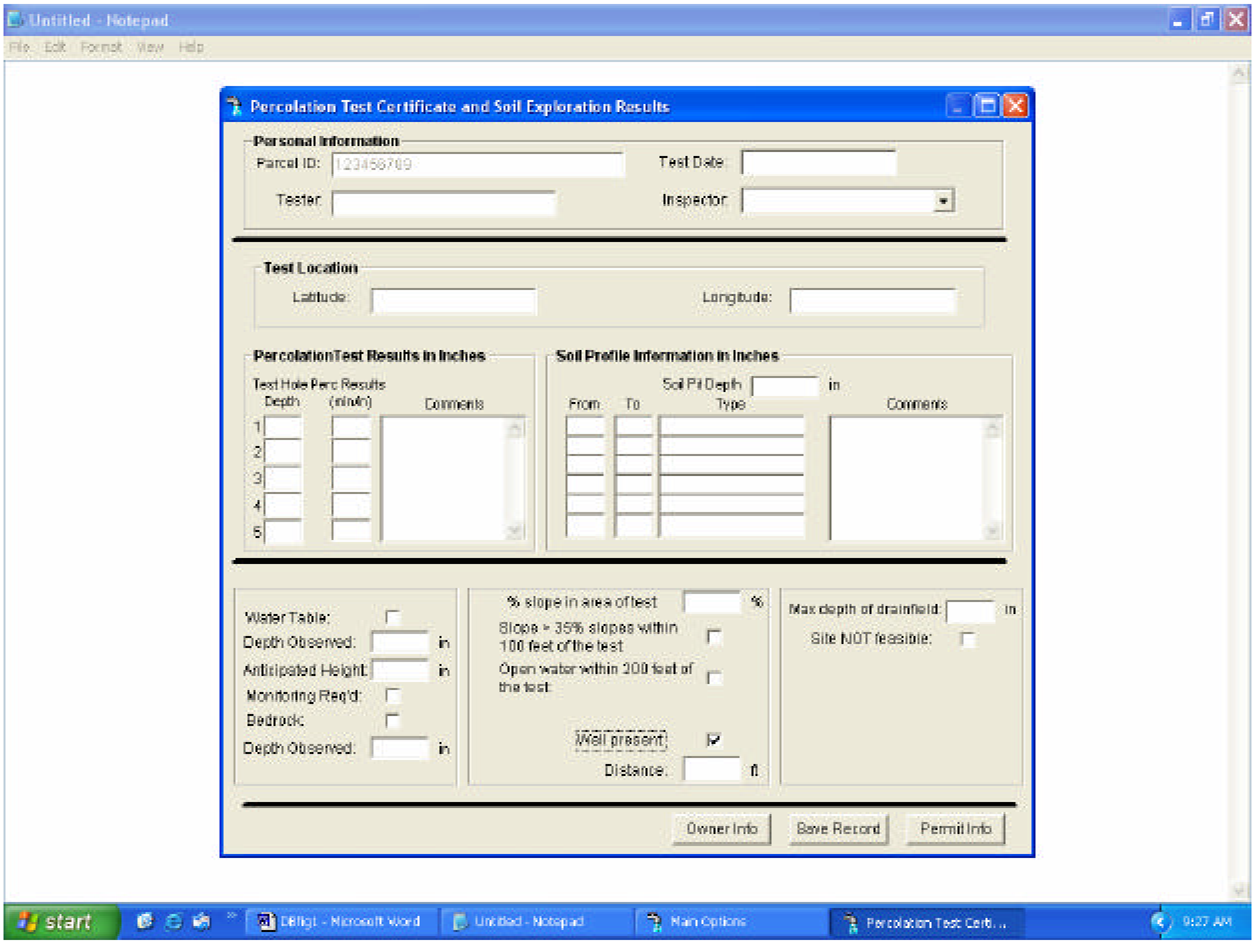

Figure 6. On-site Database percolation test results data entry form showing the optional "Distance" box when the "Well present" checkbox is selected.

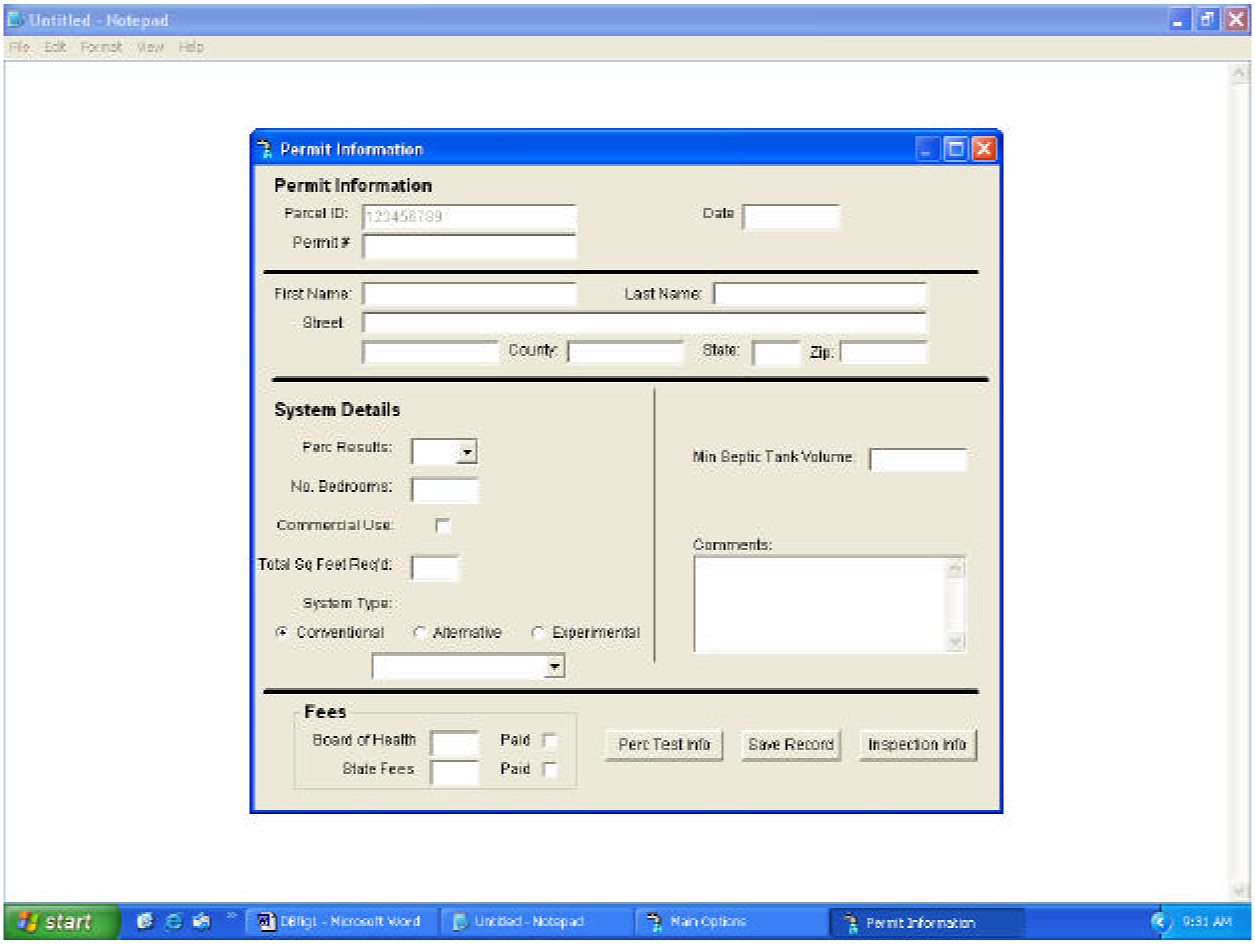

Figure 7. On-Site Database permit information input form.

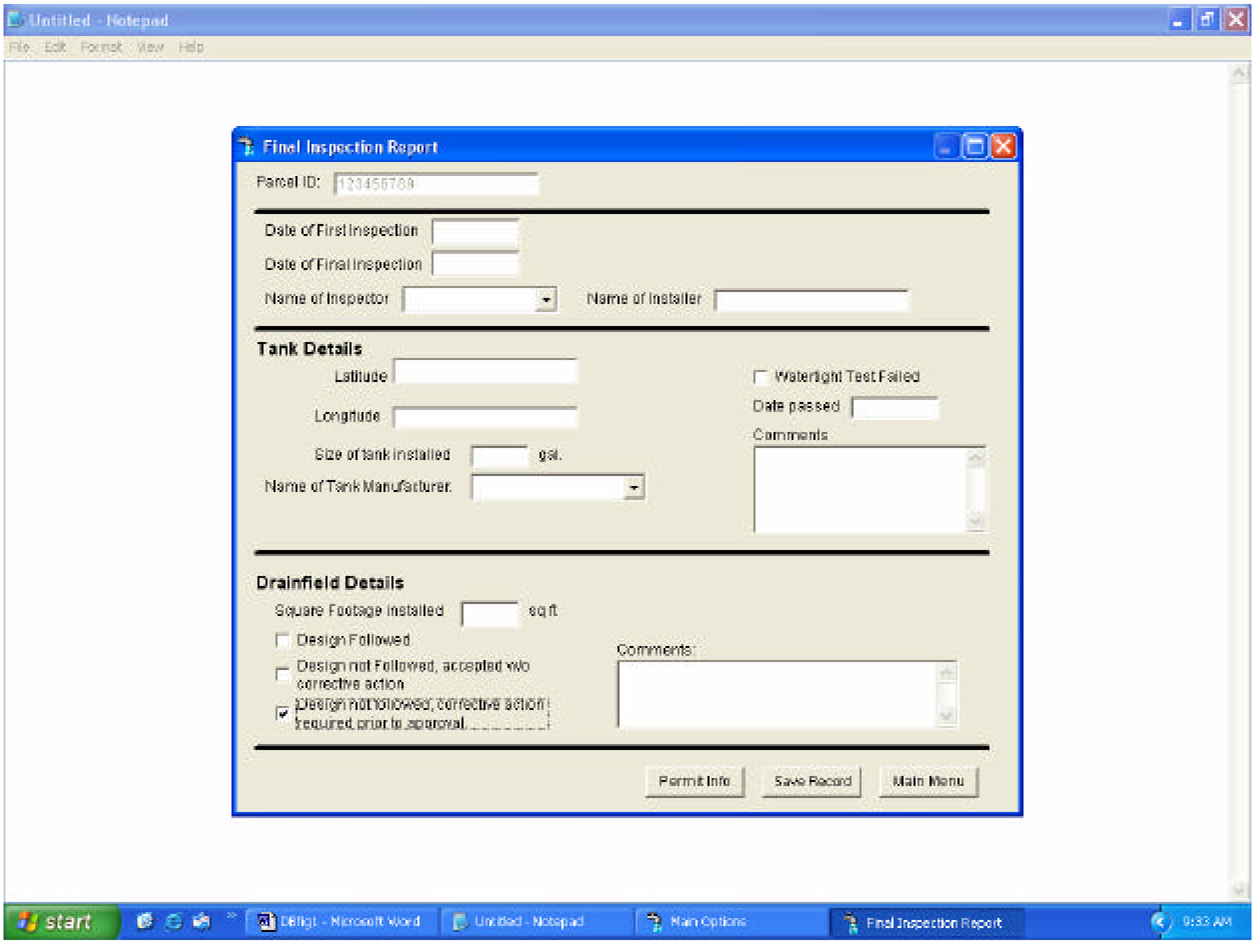

Figure 8. On-Site Database final inspection report information input form showing the optional comments box when the “Design not followed…” check box is selected.

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